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PROBABILITY DISTRIBUTION OF RECEIVED INTERFERENCE LEVELS IN THE HF BAND

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ABSTRACT

HF interference typically spans a wide dynamic range and often has a high density of detectable interferers. In the design and evaluation of communications systems it is often useful to be able to characterize the HF environment by means of an analytic model. Based upon a series of recent measurements of the HF environment, we have concluded that a lognormal distribution is a reasonable model of the observed HF interference. These data were collected using a wideband (2 MHz), high dynamic range spectrum analysis system, and consisted of short-term time averages of the magnitudes of FFT bin outputs spaced at 610 Hz. Spectral plots and associated probability distributions are presented spanning a frequency range from 1.5 to 19 MHz for various averaging parameters. In almost all cases, the distributions of the bin averages were found to be well modeled by the lognormal distribution for levels well above the background noise. In some cases, the fit was excellent over a 50 dB range of levels.

INTRODUCTION

While it is well known that received interference levels in the HF band typically span a wide dynamic range and the density of detectable interferers often is very high in active portions of the band, there seems to be relatively little quantitative data on the probability distribution of short-term average interference power over wide bandwidths. Furthermore, some of the reported results appear on the surface, at least, to be contradictory in that they seem to show different models for the interference cumulative distribution function (CDF).[1,2] Gibson and Arnett found that their data generally fit a lognormal distribution quite well, whereas Perry and Abraham, using somewhat different test conditions, obtained results that were linear functions of the form $p(x) = Ax^B$ over a wide range of interference power level x.

We have recently performed independent measurements that tend to support a lognormal model of interference CDF. Measurements of the CDFs over a 2 MHz bandwidth made in both summer and winter of 1989 near Boston, Massachusetts generally showed a good fit to lognormal distributions with standard deviation parameters ranging from about 19 to 23 dB. Furthermore, our results indicate that the CDF for a given 2 MHz band is almost unaffected by the averaging time of individual frequency bins and that they are stationary over periods of at least several minutes.

The experimental equipment and the test approach used are described in the section below. In the next section, we present the results of the experimental measurements and in fourth section we discuss a possible rationale for the observed lognormal distribution of interferers. The conclusions of the research are presented in the final section.

EXPERIMENTAL SETUP AND APPROACH

Figure 1 shows a simplified block diagram of the experimental equipment. A 20-foot vertical whip antenna feeds a wideband HF receiver whose output is a band slightly wider than 2.0 MHz centered at 1.25 MHz. The result is digitized at a 5 MHz rate using a 14-bit A/D converter, blocked into 50% overlapping 8192-point blocks, windowed, and processed in real time using an 8192-point FFT processor. The magnitudes of the resulting frequency bin outputs are calculated and, optionally, are averaged over multiple FFTs to produce a single sample (revisit) of the spectrum. In the measurements presented here, only the central 2 MHz portion of the band was retained to assure that the receiver gain was flat over the analysis band. The resulting spectra are saved to a computer disk file for later non-realtime processing.

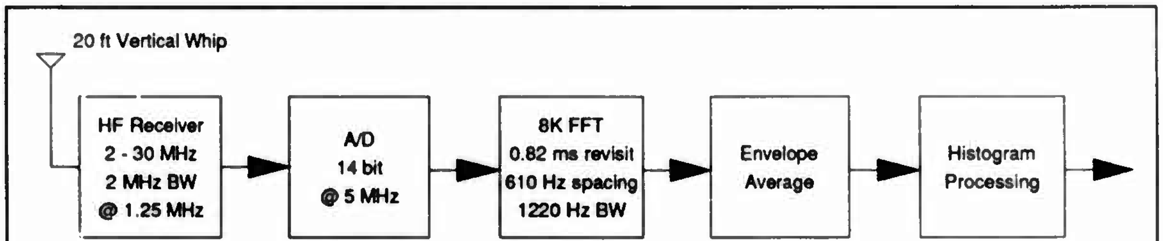

Figure 1. Block Diagram of Experiment Setup

The system is designed to provide an instantaneous dynamic range of about 120 dB at the output of the FFT. Before each collection, the input attenuator is adjusted manually to assure that overload does not occur in the receiver or the A/D converter and that the total output noise is dominated by input noise.

Because of the overlapped operation, a new FFT is produced every 0.82 ms. The resulting frequency bin spacing is about 610 Hz, but the effective bin width is about twice this because of the window, which is a Nuttal window with -92 dB worst-case sidelobes. The non-realtime processing consists of converting the averaged amplitude values into decibel values and forming histograms of all or downsampled portions of the data.

Data were collected in April and December of 1989. The earlier April measurements consisted of one second averages of magnitude spectra made at center frequencies 6, 8, 10, 12, 14, 15, 16, 18, and 22 MHz. The subsequent December collections were more comprehensive in that they used longer runs and used a variety of spectral averaging times. The December collections included experiments with a total observation interval spanning 7.1 minutes, measurements made at 5, 7, 9, 11, 13, 15, 17 and 19 MHz and envelope averaging times of 209 ms (256 FFTs). The December collections also included a separate series of collections made at 15 MHz using envelope averages over 1, 16, and 256 successive FFTs. The observation interval for these experiments also spanned 7.1 minutes with the total of the three experiments conducted within a 30 minute period. The data presented herein is primarily selected from the December experiments, although the conclusions are based upon both sets of data.

EXPERIMENTAL RESULTS

Figures 2 and 3 show typical examples of the CDFs obtained at 9 and 11 MHz plotted on a normal probability scale, and Figures 4 and 5 show snapshots of the corresponding interference spectra. In each of Figures 2 and 3, six CDFs formed from the same 7.1 minute collection are overlaid

to show the effect of changing the number of data points included in the CDF and to demonstrate stationarity of the results over that period of time. The raw data in these cases consisted of 2048 averaged spectra (revisits) each consisting of a spectral magnitude averaged over 256 FFTs (209 ms).

In one case, the CDF was formed from the first revisit alone (i.e., the first 209 ms of the 7.1 minute interval). The other five CDFs were obtained by downsampling the 2048 revisits to save 64, 128, 256, 512 or 1024 revisits (uniformly distributed in time over the 7.1 minute interval) and using the pooled data to construct the CDF. The CDFs based on 64 or more revisits are virtually indistinguishable, and the CDF based on a single revisit appears identical to within the random fluctuation expected from the small data set used in the histogram. This indicates stationarity of the CDF over periods of time of at least 7.1 minutes and indicates that 64 revisits are enough data to obtain stable results.

Before considering other experiment variations, we will consider the characteristics of the sets of CDF plots in Figures 2 and 3. These characteristics are similar among the other variations and are central to our conclusion that a lognormal model is applicable to HF interference. Observe that each CDF can be regarded as consisting of two distinct parts with a small transition region joining them. The upper part is the upper tail of the interference distribution, while the lower part is the lower tail of the background noise (received plus receiver generated). The composite distribution is well modelled in both cases by straight lines. To illustrate this, we have included a regression fit to the interference region of a typical CDF in each of the plots in Figures 2 and 3. Since the CDF plots use a normal probability scale, and the spectra data are all in logarithm format (i.e., in dB), each linear region can be regarded as approximately Gaussian. In the section following the description of the remaining experiment variations, we discuss rationale for the observed linearity for each region independently.

Figure 6 shows CDFs of data taken at 13 MHz that further demonstrate the stationarity of the CDF with time. Here, each of five CDFs was calculated using a different 128 revisit subset of the 2048 revisits collected in a 7.1 minute period. As before, each revisit consists of a 209 ms time average of the FFT bin output envelopes, with each 128 revisit subset spanning about 26.7 s. These subsets are uniformly spaced in time over the 7.1 minute total observation interval. Note that the CDFs are nearly identical except at the extreme upper tails of the distribution.

Another interesting result observed is that the CDF of the interference does not seem to depend on the envelope averaging time, at least for short averaging times. Figure 7 shows the results of measurements made at 15 MHz using three different values of envelope averaging time: no averaging (0.8 ms sample), 16 FFTs (13 ms), and 256 FFTs (209 ms). Each CDF was based on 128 revisits (of 0.8 ms, 13 ms, or 209 ms, as appropriate) equally spaced over a 7.1 minute total observation interval, and the three measurements were taken one after the other within a total period of about 30 minutes. The results are nearly identical in the interference region of the CDF, and the differences in the noise are as expected, since the distribution of an unaveraged magnitude spectrum will be Rayleigh (assuming white Gaussian input noise) whereas the averaged magnitude spectrum tends to Gaussian with increasing number of spectral samples averaged.

Figure 8 summarizes the results of measurements made over eight 2 MHz frequency bands on the evening of 28 December 1989. Each curve is the result of 128 revisits taken over a 7.1 minute period with 256 magnitudes averaged per revisit. The entire set of data was taken within a 90 minute period. Note that in almost all cases the interference portion of the CDF can be well approximated by a straight line except near the upper tail of the distribution. The noise portions of all of the CDFs also can be approximated by a straight line, indicating that the noise in each band was essentially white. No significance should be attached to the horizontal displacement of the curves since this was the result of operator adjustment of the input attenuator to optimize the dynamic range of the system at each frequency.

Figure 9 shows best and worst straight line fits to the data of Figure 8. These are the results of linear regression over data ranges chosen somewhat subjectively to emphasize the fit to a lognormal model. The best case (9 MHz) gave an excellent fit over a range of almost 60 dB. Even the worst case (19 MHz) gave an acceptable fit over a 25 dB range.

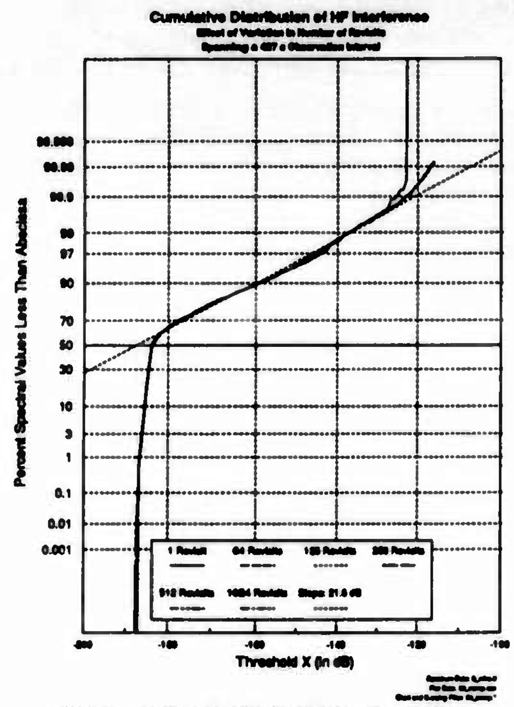

Figure 2. CDF At 9 MHz For Varying Sample Size
(7.1 m Observation Interval)

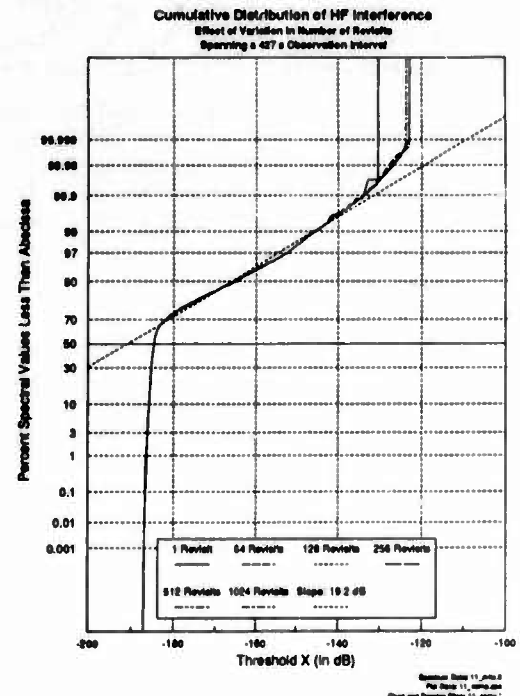

Figure 3. CDF At 11 MHz For Varying Sample Size
(7.1 m Observation Interval)

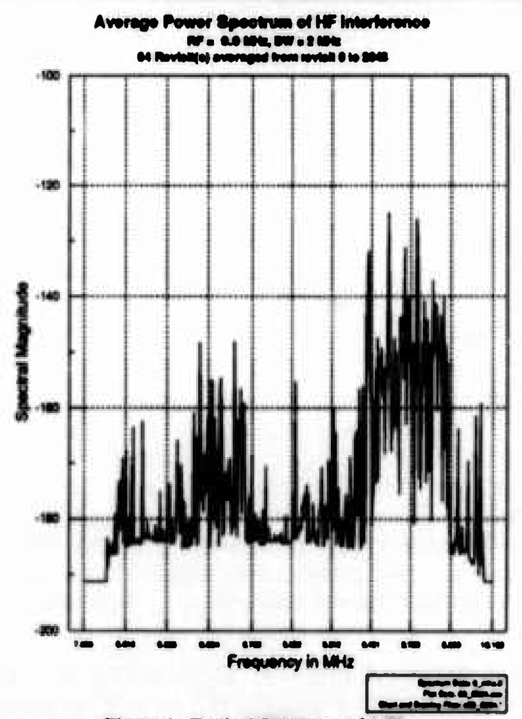

Figure 4. Typical Spectrum at 9 MHz

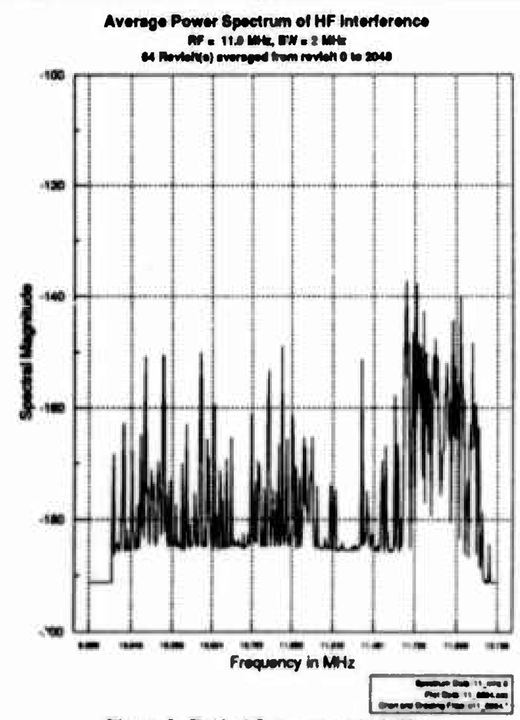

Figure 5. Typical Spectrum at 11 MHz

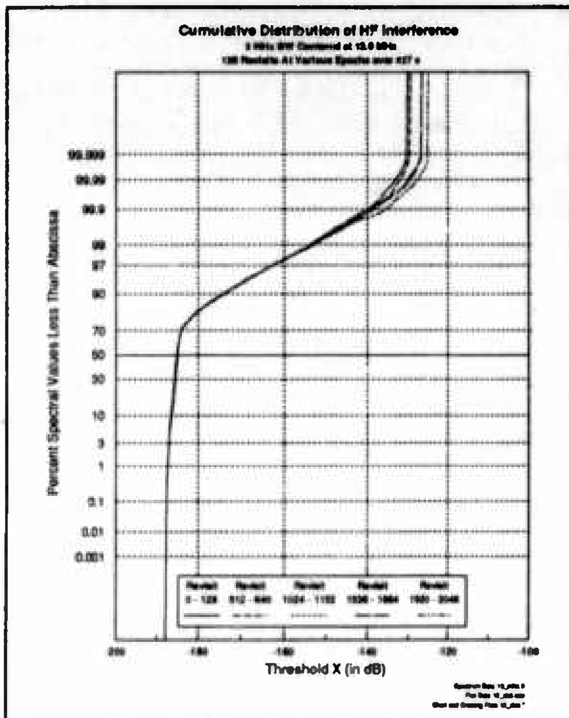

Figure 6. CDF at 13 MHz for Various 26.7 s Epochs Selected From 7.1 m

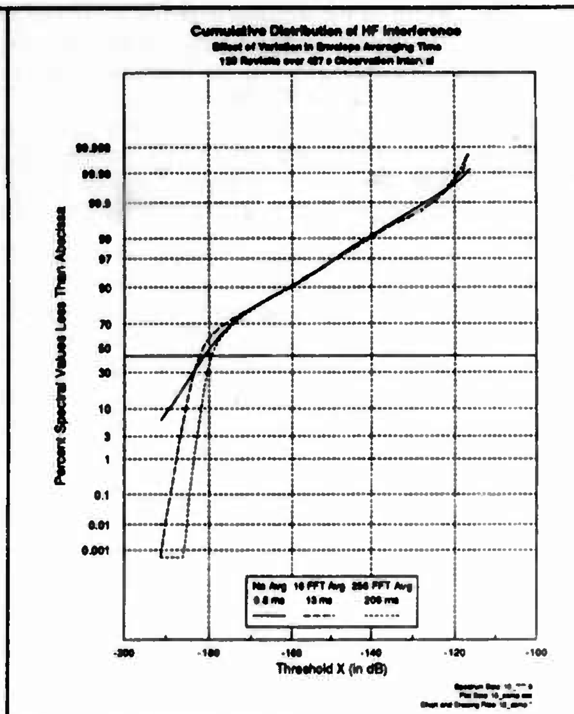

Figure 7. CDF at 15 MHz for Various Averaging Times Uniformly Distributed Over 7.1 m

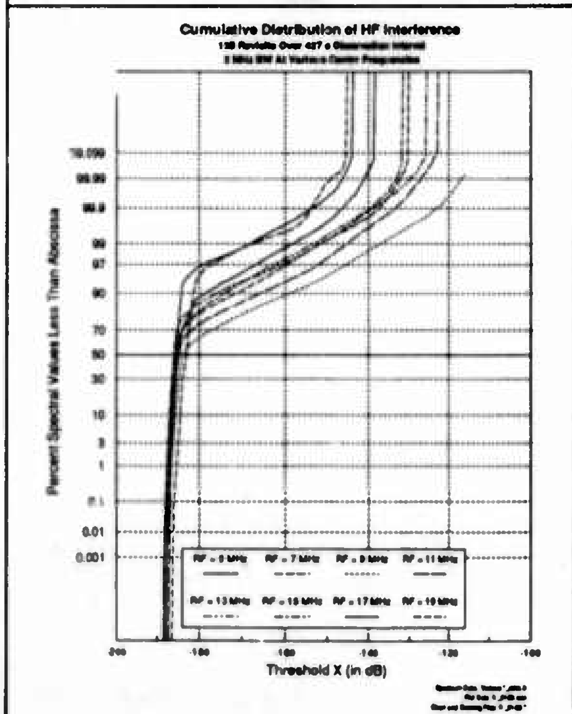

Figure 8. CDF For Various Center Frequencies

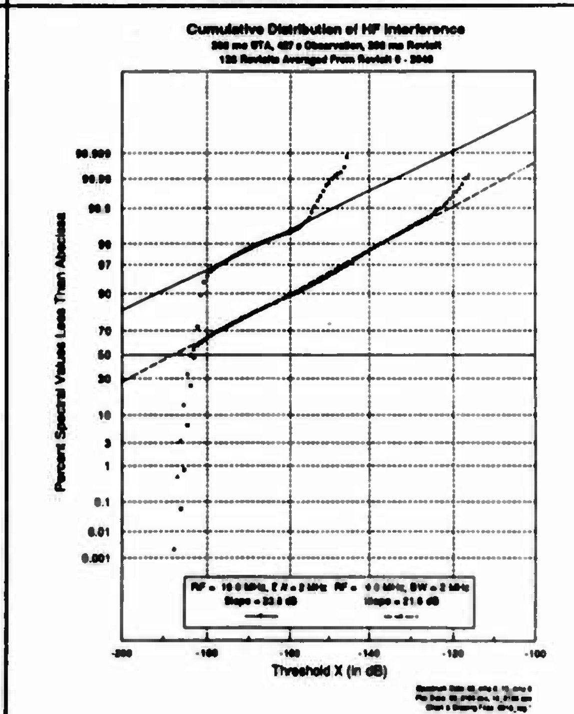

Figure 9. Regression Fit for CDF at 9 and 19 MHz

The slopes of the straight line fits are inversely proportional to the standard deviation S in decibels of the approximating Gaussian distribution. These standard deviations were found to be well clustered in both the April and the December data. The April data yielded an average value of 19.7 dB and a standard deviation of 2.4 dB for S. The December data yielded 20.1 dB and 1.8 dB for the mean and standard deviation of S. We have also estimated the slope of CDF data presented by Gibson and Arnett from the plots in Reference 1 to be approximately 20 dB. These results suggest that a Gaussian distribution of signal level in decibels with a 20 dB standard deviation would constitute a reasonable empirical model for the distribution of HF interference.

To complete the model, we need to specify the vertical axis intercept or other equivalent parameter of the straight-line fit. One convenient parameter is the probability value at which the extrapolated noise distribution intersects the straight-line approximation to the interference distribution. This point represents the fraction of all frequency bins that are dominated by noise rather than interference, and is an intuitively meaningful parameter. This parameter varied over a wide range in our experiments, as might be expected, since both the received signal level and the received noise vary significantly with frequency and time of day and year. Also the noise level is strongly dependent on the local noise environment, which in our case is a suburban industrial area.

ORIGIN OF THE LOGNORMAL DISTRIBUTION OF INTERFERENCE LEVELS

The observed fit of the interference CDFs to a lognormal distribution is too consistent over time and frequency to be chance and clearly must be the result of some robust mechanism.

Consider first the background noise region. In this case, the linearity of the log spectral data is indicative of a lognormal process; however, since the slope is very steep, it is also indicative of a distribution wherein the standard deviation is small relative to the mean. It is our supposition that the background noise spectrum is approximately Gaussian. To the extent that the noise in the 2 MHz band is white and suitably well behaved, the frequency bins of the average of a large number of magnitude spectra (i.e., 256 spectra) will be approximately jointly Gaussianly distributed by virtue of the central limit theorem. Furthermore, since the normalized standard deviation of the averaged bins will be very small, the distribution in dB also will be approximately lognormal and will plot as a straight line on a normal probability scale.

To show this, we consider a Gaussian variate x assumed to be normalized to unit mean. We write it as

$$x = 1 + u$$

where u is a zero-mean Gaussian random variable with standard deviation very much smaller than unity. The logarithm of x can be expressed in a Taylor's series as

$$\ln(x) = \ln(1+u) = u - \frac{u^2}{2} + \dots$$

Since u is almost always much smaller than unity, all but the leading term of the series can be ignored, leading to the approximation $\ln(x) = u$. Therefore, since u is Gaussian, $\ln(x)$ will be approximately Gaussian.

Consider now the CDF region attributed to the interference levels. An obvious candidate here is the central limit theorem applied to various multiplicative random effects (additive in dBs) that determine the received interference level. There are more of these than might be supposed on first consideration and include:

- Rated transmitter output power
- Loading factor - fraction of transmitter power capability actually used, as determined by type of modulation and modulation source

- Transmit antenna gain in direction of receiver
- Average propagation loss from transmitter to receiver - product of inverse-square law loss and reflection losses at the ionosphere and ground
- Instantaneous fading gain for the path
- Receiver antenna gain in direction of the transmitter
- Fraction of interference power intercepted by a given frequency bin - depends on bin width and modulation type

While these are not all completely independent of each other, clearly there are several essentially independent multiplicative variables involved, each of which has a range of variation of several dB. Thus it would not be surprising that the convolution of their individual distributions (in units of dBs) would tend to a Gaussian distribution.

As a test, we postulated distribution functions for each of the above quantities expressed in decibels, and numerically convolved them to obtain a composite distribution for the received interference. The postulated distributions, described via the parameters in Table 1, are not offered as necessarily realistic, and in some cases are greatly oversimplified. However, they will serve to illustrate the principle. Figure 10 shows the resulting distribution plotted on a normal probability scale. It is seen to be reasonably linear over 120 dB of range. The standard deviation is about 15 dB, somewhat smaller than the experimental data, which suggests that some of the postulated distributions of Table 1 may have been too narrow. Note that this convolved distribution does not include a component representative of the broadband background noise so that a second steeply sloped region is not present.

Table 1
Postulated Component Distributions Contributing to Received Interference Distribution

Rated transmitter output peak envelope power: Six discrete values with following probabilities:

Power	Probability	Power	Probability
10 W	0.05	1 kW	0.3
100 W	0.1	5 kW	0.25
500 W	0.2	10 kW	0.1

Loading factor: Four discrete values with following probabilities:

Load Factor	Probability	Signal Type
1.0	0.3	FSK
0.5	0.5	CW Morse, AM Voice
0.1	0.1	VFT
0.05	0.1	SSB Voice

Transmit antenna gain: Cosine directivity pattern (short horizontal dipole)

Average propagation loss: Two factors assumed. One was inverse-square loss corresponding to transmitters uniformly distributed over earth surface. The other was ionospheric and ground reflection loss modelled as uniformly distributed from 0 to 6 dB.

Instantaneous fading gain: Rayleigh envelope distribution

Receiver antenna gain: Omnidirectional

Fraction of interference power in a single bin: Uniform distribution in dB ranging from 0 to 10 dB.

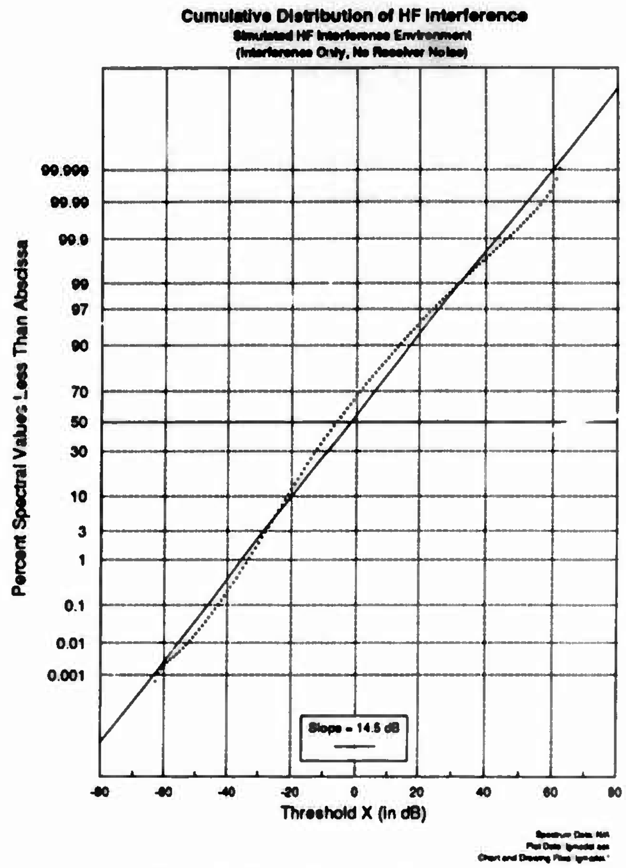

Figure 10. CDF of Simulated HF Model

CONCLUSIONS

Based upon both experimental data collected in the metropolitan Boston area and a theoretical distribution obtained by convolving the distribution of some hypothetical emitter characteristics, we have concluded that the typical HF interference levels can be well modeled as arising from a lognormal random process. Furthermore we have observed that the model is surprisingly robust with respect to several observation parameters including the envelope averaging time used to estimate the instantaneous interference level, the time epoch of the observation (at least over the space of several minutes), and the frequency of the particular 2 MHz wide observation spectrum. Our proposed model is consistent with the observations and conclusions by Gibson and Arnett drawn from HF spectrum occupancy measurements in Southern England and reported in [1]. This suggests that the model is not somehow tied into the HF environment conditions specific to the New England area of the U.S., and may therefore be globally applicable. An advantage of using the proposed lognormal model is that the combination of the background noise and interference characteristics can be specified with three parameters: the mean and variance of the lognormal process representing the interference and the mean power level of a broadband process representing the background and receiver noise.

1. A. J. Gibson and L. Arnett, "New HF Spectrum Occupancy Measurements in Southern England", Fourth International Conference on HF Radio Systems and Techniques, 1988.

2. B. D. Perry and L. G. Abraham, "A Wideband HF Interference and Noise Model Based on Measured Data", Fourth International Conference on HF Radio Systems and Techniques, 1988.